

WHAT IS CLAIMED IS:

1. An organ manipulation apparatus, including:  
at least one suction member having an inner surface and an outer surface, wherein the suction member is configured to exert sufficient suction force on an organ to move the organ when the suction member is placed against the organ, a pressure differential is established between the inner surface and the outer surface, and the suction member is moved;

a support structure; and

a compliant joint coupled between the suction member and the support structure, wherein the support structure and the compliant joint are configured to support the suction member, with the organ supported in a retracted position by the suction member, such that the suction member has freedom to move at least along an axis of the suction member relative to the support structure.

2. The apparatus of claim 1, wherein the support structure and the compliant joint are configured to support the suction member with the organ suspended from the suction member in the retracted position, and with the suction member having freedom to move at least vertically relative to the support structure in response to normal movement of the organ.

3. The apparatus of claim 1, wherein the organ is a beating heart, and the support structure, the compliant joint, and the suction member are configured to suspend the organ below the suction member in the retracted position, with the suction member having freedom to move at least vertically

relative to the support structure in response to beating movement of the organ.

4. The apparatus of claim 3, wherein the beating heart has an apex, and the suction member is configured to conform to, and exert suction on, the apex of the beating heart.

5. The apparatus of claim 3, wherein the suction member is a suction cup including:

a concave shell attached to the compliant joint, said shell defining the inner surface and the outer surface and a periphery between the inner surface and the outer surface; and

a seal mounted to the shell so as to extend around the periphery.

6. The apparatus of claim 5, wherein the seal is made of biocompatible foam.

7. The apparatus of claim 5, wherein the shell is a rigid shell.

8. The apparatus of claim 7, wherein the suction cup also includes absorbent material which lines at least a portion of the inner surface.

9. The apparatus of claim 5, wherein the shell is flexible but has a shape memory, whereby the shell is deformable in response to external force into an organ-conforming shape which conforms to a surface of the beating heart and remains in the organ-conforming shape following exertion of the external force.

10. The apparatus of claim 9, wherein the shell comprises a continuous sheet of elastomeric material coated over a deformable metal mesh.

11. The apparatus of claim 5, wherein the inner surface of the shell is lined with smooth and soft material.

12. The apparatus of claim 5, wherein the shell is made of smooth and soft material.

13. The apparatus of claim 12, wherein the suction cup also includes absorbent material which lines at least a portion of the inner surface of the shell.

14. The apparatus of claim 1, wherein the suction member is shaped and configured to assert sufficient suction to a beating heart to retract the beating heart from a first position to the retracted position.

15. The apparatus of claim 1, wherein the support structure and the compliant joint are configured to support the suction member, with the organ suspended therefrom and with the suction member having freedom to rotate, with at least a portion of the organ, about a vertical axis relative to the support structure.

16. The apparatus of claim 1, wherein the support structure and the compliant joint are configured to support the suction member, with the organ suspended therefrom and with the suction member having freedom to swing, with at least a portion of

the organ, in a vertical plane relative to the support structure.

17. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, the compliant joint is a sliding ball joint.

18. The apparatus of claim 17, wherein the sliding ball joint includes:

- a ball attached to the arm; and

- a member support element mounted to the suction member, said support element defining two parallel grooves along which the ball is free to translate.

19. The apparatus of claim 17, wherein the fixed structure is a sternal retractor.

20. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, and wherein the compliant joint includes:

- a support element mounted to the member, wherein the support element defines two parallel slots; and

- a pair of pins mounted to the arm in such a position that each of the pins slides in a different one of the slots.

21. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, and wherein the compliant joint is a spring assembly coupled between the arm and the suction member.

22. The apparatus of claim 21, wherein the spring assembly includes:

a chamber defining a volume maintained at low pressure during exertion of suction force on the organ;

a piston mounted in the chamber at one end of the volume with freedom to translate relative to the chamber, said piston having a first side facing the volume and a second side facing away from the volume; and

an element having fixed maximum length which couples the piston to the suction member, wherein the piston is biased in an equilibrium position in the chamber by a first force coupled through the element to the piston from the organ, and a piston suction force exerted on the piston in a direction opposite to the first force as a result of maintenance of lower pressure on the first side of the piston than on the second side of the piston.

23. The apparatus of claim 21, wherein the spring assembly is configured to maintain a constant retraction force on the suction member.

24. The apparatus of claim 1, also including:

a suction line coupled to the suction member;

and

a low-pressure reservoir coupled to the suction line and configured to be coupled to a vacuum source, said reservoir having sufficient volume to continue to maintain assertion of said sufficient suction force for a significant time in the event of interruption of suction flow from the vacuum source to the suction line.

25. The apparatus of claim 24, also including:

a vacuum regulator coupled to the suction line between the suction member and the reservoir, and configured to control the pressure differential.

26. The apparatus of claim 1, including:

multiple suction members, each having an inner surface and an outer surface, wherein the suction members are configured to exert sufficient suction force on the organ to move the organ when the suction members are placed against the organ, said pressure differential is established between the inner surface and the outer surface of each of said members, and said members are moved,

wherein the compliant joint is coupled between the support structure and each of the suction members, and wherein the support structure and the compliant joint are configured to support the suction members with the organ suspended from the suction members in the retracted position, and with each of the suction members having freedom to move, at least vertically, relative to the support structure in response to normal movement of the organ.

27. The apparatus of claim 26, wherein the compliant joint includes:

a set of hinged fingers, each of the fingers having a distal end to which a different one of the suction members is mounted.

28. The apparatus of claim 1, wherein the suction member includes:

a flexible enclosure having a first portion configured to be coupled to a vacuum source, and a second portion which is permeable to gas; and

pellets in the enclosure, whereby evacuation of the enclosure when the second portion of the bag is

pressed against the organ causes the pellets in the evacuated enclosure to form a rigid structure which conforms to the organ.

29. The apparatus of claim 1, wherein the compliant joint has a nonlocking state in which the suction member has freedom to move along the axis of the suction member relative to the support structure, and a locking state in which the suction member is not free to move along the axis of the suction member relative to the support structure.

30. The apparatus of claim 29, wherein the compliant joint includes a latch which is movable between a first position and a second position, the compliant joint is in the locking state when the latch is in the first position, and the compliant joint is in the nonlocking state when the latch is in the second position.

31. The apparatus of claim 1, wherein the compliant joint includes a spring, wherein the spring is positioned in contact with the suction member in such a position that the spring damps oscillation of the suction member relative to the support structure.

32. The apparatus of claim 1, wherein the suction member is a suction cup including:

- a rigid core; and

- a flexible shell supported by the rigid core, wherein the shell has a generally concave distal surface, and the rigid core is coupled to the compliant joint so as to have freedom to move at least along the axis of the suction member relative to the support structure.

33. The apparatus of claim 32, wherein the distal surface of the shell has a periphery, and the shell has a flexible flange portion which extend around the periphery, the apparatus also including:

a seal mounted to the flexible flange portion of the shell.

34. The apparatus of claim 32, wherein the rigid core is made of plastic and the shell is cup-shaped and made of silicone.

35. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, the arm has a flexible state and a rigid state, and the arm comprises:

a cable; and

ball joints threaded along the cable, each of the ball joints having a convex surface, a concave socket surface, a length, and a diameter, wherein the socket surface is shaped for receiving the convex surface of an adjacent one of the ball joints, and the diameter is greater than the length.

36. The apparatus of claim 35, wherein the ratio of the length to the diameter is at least substantially equal to 0.345/0.460.

36. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, the arm has a flexible state and a rigid state, and the arm comprises:

a cable; and

ball joints threaded along the cable, each of the ball joints having a convex surface and a concave



socket surface, wherein each of the ball joints is molded from plastic and at least a first portion of the concave socket surface is molded with a texture which provides sufficiently high friction to lock the arm in the rigid state when the convex ball surface of an adjacent one of the ball joints is tightened against the first portion of the concave socket surface.

37. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, the arm has a flexible state and a rigid state, and the arm comprises:

a cable; and

ball joints threaded along the cable, each of the ball joints having a main portion defining a convex surface and part of a concave socket surface, and an insert portion defining a remaining part of the concave socket surface, wherein the main portion is molded from hard plastic and the insert portion is molded from a material having greater friction than does the hard plastic.

38. The apparatus of claim 37, wherein the insert portion is molded from a thermoplastic or silicone elastomer.

39. The apparatus of claim 38, wherein the insert portion has an annular shape and comprises thermoplastic or silicone elastomer material having Shore A durometer in the range 50 to 90.

40. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, the

arm has a flexible state and a rigid state, and the arm comprises:

a cable; and

ball joints threaded along the cable, each of the ball joints having a first portion defining a convex surface and part of a concave socket surface, and a second portion defining a remaining part of the concave socket surface, wherein the first portion of each of the ball joints is molded hard plastic and the second portion is molded thermoplastic or silicone elastomer.

41. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, the arm has a flexible state and a rigid state, and the arm comprises:

a cable; and

ball joints and sleeves threaded alternately along the cable, each of the ball joints defining a convex surface at each end, and each of the sleeves defining a concave socket surface at each end, wherein each of the ball joints is molded from plastic having a first hardness and each of the sleeves is molded from plastic having a second hardness different from the first hardness.

42. The apparatus of claim 41, wherein each of the ball joints is molded from polycarbonate plastic and each of the sleeves is molded from Ultem plastic.

43. The apparatus of claim 41, wherein each of the sleeves is molded from polycarbonate plastic and each of the ball joints is molded from Ultem plastic.

44. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, the arm has a flexible state and a rigid state, and the arm comprises:

- a cable; and

- a first set of ball joints and a second set of ball joints threaded alternately along the cable, wherein each of the ball joints in the first set and the second set defines a convex surface and a concave socket surface, each of the ball joints in the first set is molded from plastic having a first hardness and each of the ball joints in the second set is molded from plastic having a second hardness different from the first hardness.

45. The apparatus of claim 44, wherein each of the ball joints in the first set is molded from polycarbonate plastic and each of the ball joints in the second set is molded from Ultem plastic.

46. The apparatus of claim 1, wherein the support structure includes a fixed structure and an arm adjustably mounted to the fixed structure, the compliant joint is a sliding ball joint, and said sliding ball joint includes:

- a ball attached to the arm;

- a member support element mounted to the suction member, said support element defining two parallel grooves along which the ball is free to translate; and

- a spring coupled between the ball and the member support element.

47. The apparatus of claim 46, wherein the ball and the member support element are marked in such a

manner as to implement a force gauge which provides a visual indication of spring force being exerted by the spring on said member support element.

48. An organ manipulation apparatus, including:  
at least one bio-absorbable disc with an adhesive surface configured to be adhered to an organ, wherein the disc is configured to exert sufficient traction force on the organ to move the organ when the adhesive surface is pressed against the organ and said disc is moved;

a support structure; and

a compliant joint coupled between the disc and the support structure, wherein the support structure and the compliant joint are configured to support the disc with the organ suspended from the disc in a retracted position, and with the disc having freedom to move, at least vertically, relative to the support structure.

49. The apparatus of claim 48, wherein the organ is a beating heart, and the support structure, the compliant joint, and the disc are configured to suspend the organ below the disc in the retracted position, with the disc having freedom to move at least vertically relative to the support structure in response to beating movement of the organ.

50. A method for compliant retraction of an organ, including the steps of:

(a) retracting the organ by exerting suction thereon using a suction member coupled to a mounting element, in such a manner that the suction member has freedom to move at least along an axis of said suction member relative to the mounting element in response to normal movement of the organ; and

(b) maintaining the organ in a retracted position by exerting suction thereon using the suction member while said suction member is coupled to the mounting element, in such a manner that said suction member has freedom to move at least along the axis of said suction member relative to the mounting element.

51. The method of claim 50, wherein the suction member is a single suction cup, the organ is a beating heart, and step (b) includes the step of suspending the heart from the suction cup in the retracted position using suction in such a manner that the suction member has freedom to move at least vertically relative to the mounting element in response to normal beating movement of the heart.

52. The method of claim 51, wherein the beating heart has an apex, the suction cup is configured to conform to and exert suction on the apex of the beating heart, and step (a) includes the steps of:

affixing the suction cup to the heart at a position of the heart concentric with said apex of the heart;

applying suction to the heart by coupling the suction member to a vacuum source; and

moving the suction member to retract the heart.

53. The method of claim 50, wherein the suction member comprises multiple suction cups, the organ is a beating heart, and step (b) includes the step of suspending the heart from the multiple suction members in the retracted position using suction in such a manner that each of the suction members has freedom to move at least vertically relative to the

mounting element in response to normal beating movement of the heart.

54. A method for compliant retraction of an organ, including the steps of:

(a) retracting the organ by exerting traction thereon using a bio-absorbable disc having an adhesive surface affixed to the organ, wherein the disc is coupled to a mounting element in such a manner that the disc has freedom to move at least along an axis of said disc relative to the mounting element; and

(b) maintaining the organ in a retracted position by exerting traction thereon while the disc is coupled to the mounting element, in such a manner that the disc has freedom to move, at least along the axis of said disc relative to the mounting element.

55. The method of claim 54, wherein the organ is a beating heart, and step (b) includes the step of suspending the heart from the disc in the retracted position in such a manner that the disc has freedom to move at least vertically relative to the mounting element in response to normal beating movement of the heart.

56. A locking arm having a flexible state and a rigid state for use in an organ manipulator apparatus, the arm comprising:

a cable; and

ball joints threaded along the cable, each of the ball joints having a convex surface, a concave socket surface, a length, and a diameter, wherein the socket surface is shaped for receiving the convex surface of an adjacent one of the ball joints, and the diameter is greater than the length.

57. The arm of claim 56, wherein the ratio of the length to the diameter is at least substantially equal to 0.345/0.460.

58. A locking arm having a flexible state and a rigid state for use in an organ manipulator apparatus, the arm comprising:

- a cable; and
- ball joints threaded along the cable, each of the ball joints having a convex surface and a concave socket surface, wherein each of the ball joints is molded from plastic and at least a first portion of the concave socket surface is molded with a texture which provides sufficiently high friction to lock the arm in the rigid state when the cable is tensioned to tighten the convex ball surface of an adjacent one of the ball joints against the first portion of the concave socket surface.

59. A locking arm having a flexible state and a rigid state for use in an organ manipulator apparatus, the arm comprising:

- a cable; and
- ball joints threaded along the cable, each of the ball joints having a main portion defining a convex surface and part of a concave socket surface, and an insert portion defining a remaining part of the concave socket surface, wherein the main portion is molded from hard plastic and the insert portion is molded from a material having greater friction than does the hard plastic.

60. The arm of claim 59, wherein the insert portion is molded from a thermoplastic or silicone elastomer.

61. The apparatus of claim 60, wherein the insert portion has an annular shape and comprises thermoplastic or silicone elastomer material having Shore A durometer in the range 50 to 90.

62. A locking arm having a flexible state and a rigid state for use in an organ manipulator apparatus, the arm comprising:

a cable; and

ball joints threaded along the cable, each of the ball joints having a first portion defining a convex surface and part of a concave socket surface, and a second portion defining a remaining part of the concave socket surface, wherein the first portion of each of the ball joints comprises molded hard plastic and the second portion comprises molded thermoplastic or silicone elastomer.

63. A locking arm having a flexible state and a rigid state for use in an organ manipulator apparatus, the arm comprising:

a cable; and

ball joints and sleeves threaded alternately along the cable, each of the ball joints defining a convex surface at each end, and each of the sleeves defining a concave socket surface at each end, wherein each of the ball joints is molded from plastic having a first hardness and each of the sleeves is molded from plastic having a second hardness different from the first hardness.

64. The arm of claim 63, wherein each of the ball joints is molded from polycarbonate plastic and each of the sleeves is molded from Ultem plastic.



65. The arm of claim 63, wherein each of the sleeves is molded from polycarbonate plastic and each of the ball joints is molded from Ultem plastic.

66. A locking arm having a flexible state and a rigid state for use in an organ manipulator apparatus, the arm comprising:

    a cable; and  
    a first set of ball joints and a second set of ball joints threaded alternately along the cable, wherein each of the ball joints in the first set and the second set defines a convex surface and a concave socket surface, each of the ball joints in the first set is molded from plastic having a first hardness and each of the ball joints in the second set is molded from plastic having a second hardness different from the first hardness.

67. The apparatus of claim 66, wherein each of the ball joints in the first set is molded from polycarbonate plastic and each of the ball joints in the second set is molded from Ultem plastic.